Final Scientific/Technical Report

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Project Title: **State-of-the-Art Beta Detection and Dosimetry**

Principle Investigator: **David M. Hamby, PhD**

Distribution Limitations: **None**

Executive Summary

The research funded by this NEER grant establishes the framework for a detailed understanding of the challenges in beta dosimetry, especially in the presence of a mixed radiation field. The work also stimulated the thinking of the research group which will lead to new concepts in digital signal processing to allow collection of detection signals and real-time analysis such that simultaneous beta and gamma spectroscopy can take place. The work described herein (with detail in the many publications that came out of this research) was conducted in a manner that provided dissertation and thesis topics for three students, one of whom was completely funded by this grant. The overall benefit of the work came in the form of a dramatic shift in signal processing that is normally conducted in analog pulse shape analysis. Analog signal processing was shown not to be feasible for this type of work; digital signal processing was a must. This, in turn, led the research team to a new understanding of pulse analysis, one in which expands the state-of-the-art in simultaneous beta and gamma spectroscopy with a single detector.

Comparison of Accomplishments with Original Goals and Objectives

Protection against beta radiation is usually a simple matter of interposing a thin layer of low-Z material between source and receptor. But if the goal is to measure beta dose rates or identify unknown radionuclides, from a mixed beta-gamma contamination event, for example, instruments specially designed for that purpose are required. Beta dosimetry is quite difficult and has been studied for decades. Several problems arise, however, including determinations of initial energies, exposure nuclides, affected tissue mass, biological damage and overexposure, self-absorption, and spatial dependencies (Miklos 2002). Tissue-equivalent thermoluminescent dosimeters (TLDs) have been used in multi-element arrays with selective filtration of varying thickness, and with methods of laser-heating for dimensional and energy-deposition depth information. Generally, spectrometers developed to measure beta-particle energy distributions possess an inherent sensitivity to gamma-ray interactions that result in distortions of the measured distributions. The design of a beta spectrometer depends largely on the measuring task; if a beta spectrum is to be measured in a mixed beta/gamma field, a separation of the beta energy from that of the gamma rays has to be carried out.

In an attempt to minimize this distortion, a method of data collection has evolved over the years whereby two separate energy distributions are measured for each mixed beta/gamma source. The first measurement is the spectrometer "open window" response to both beta particles and gamma rays. A filter, of sufficient thickness to stop incident beta particles, is then placed around the spectrometer and the gamma-ray response is measured. The incident beta-particle energy distribution is determined by stripping the second measured distribution from the first. The disadvantages of this method are that the ambient gamma-ray field must remain constant during the measurement of the two distributions, the method doubles the time required to collect data, and instability in the spectrometer can lead to discrepancies between the gamma-ray-induced pulse-height distributions.

Usuda et al. (1994a) developed a phoswich detector for simultaneous counting of alpha, beta and gamma rays. The separation of pulses induced from different radiations was carried out by using an analog pulse-shape discrimination technique. However, a difficulty arises in separation between beta and gamma rays because of the similarity of radiation interactions within the scintillators, and the formation of bremsstrahlung X rays due to hard betas. We've considered these issues in designing our phoswich detectors and in developing the foundation of our spectral analysis technique.

About ten years ago, we began development of a triple phosphor sandwich (“TPS”) detector that was to provide information for identifying and quantifying beta-emitting radionuclides (Bush-Goddard 2000). Then, based on advancements made to the Bush-Goddard design, the PI and his students developed a 2nd prototype scintillator (Kriss and Hamby 2004a) to investigate beta dosimetry in thin detector layers (Kriss and Hamby 2003; 2004b; 2004c). Expanding on what we’ve learned (Tavakoli-Farsoni and Hamby 2004a; 2004b), we have extended our initial and subsequent work to involve full characterization of a 3rd generation multi-layer phoswich unit, with high-speed digital signal analysis, followed by systems development and automation for real-time and simultaneous beta/gamma spectroscopy and dosimetry of fission-product contamination and mixed radiation fields. The prototype spectrometer is a triple-layered phoswich, similar to its predecessor, which is combined with digital pulse analysis to allow rapid and definitive pulse discrimination. With this detector and a coincidence/anti-coincidence scheme, we have the ability to eliminate gamma cross-talk between layers and characterize alpha, beta, and gamma (by interaction mechanism) energy-deposition events. Response functions for each of the three scintillators have been generated for the development of a unified detection system that is used with digital signal processing, spectral analysis schemes, and neural network pattern recognition. Our phoswich system is desirable over existing units because of its ability to differentiate incident beta from gamma radiation and provide an automated approach to beta/gamma spectroscopy and dosimetry.

Our triple-layer design is useful for several reasons. Although a Si(Li) detector is most often the best detector for beta spectroscopy in the laboratory, it requires a continuous source of liquid nitrogen and, in the field, this source may not be readily available. Spectral information from thick solid-state detectors (necessary for the identification of ^{90}Sr/Y) can be distorted since they generate varying pulse shapes dependent on the interaction location within the substrate. Additionally, the solid-state detectors inherently possess relatively large dead layers or contain thick detector casings, thereby eliminating useful spectroscopy of low-energy betas. The phoswich system is capable of beta and gamma spectroscopy and dosimetry over a large range of beta energies, including low-energy emissions down to about 25 keV and high-energy electrons up to about 3.2 MeV.

We employ digital pulse shape discrimination with our phoswich detector to differentiate between the contributions to light output from different radiation types in a mixed beta/gamma field, thus allowing two individual spectra from gamma and beta particles to be collected simultaneously. As originally proposed, our software-based spectral manipulation routines are coded as firmware using FPGA (field-programmable gate array) digital filtering, thus drastically increasing spectral processing speeds.

Our over-riding objective is to provide an automated, real-time beta spectroscopy and dosimetry system for use in mixed beta/gamma radiation fields. Efforts herein have focused on identifying and quantifying the beta-emitting nuclides in the presence of gamma-ray interference. The digital spectrometer we've developed is capable of recording separate beta and gamma-ray energy distributions, with minimal interference, using a three-layer phoswich. Gamma-ray spectra provide additional information for beta-emitting nuclide identification and quantification. Pulse shape discrimination is performed using a state-of-the-art digital signal processing technique developed and demonstrated in our laboratory. In building on our previous work, we have enhanced our beta spectroscopy/dosimetry system by using simultaneous collection of beta/gamma spectra to identify/quantify beta emitters, combined with digital signal processing and software enhanced techniques for high-speed real time spectral analysis.

Background

Phoswich Detectors. A phoswich detector is generally thought of as one in which two different scintillators have been optically coupled to each other and to a single photo-collection device. The two scintillators are referred to as a phosphor sandwich, hence the name "phoswich". Scintillators in the sandwich are chosen specifically so that their light-emission decay times are significantly different. Thus, it can be determined in which phosphor a given interaction takes place. This allows rudimentary discrimination by particle type using pulse-shape analysis techniques (Wissink et al. 1997; Lautridou et al. 1996; Frontera et al. 1993). Sodium iodide (NaI:Tl) and cesium iodide (CsI:Na) are often chosen as the two sandwich materials because their decay times are quite different, and pulses arising from only one scintillation are easily distinguished from those with both components, using the pulse shape discrimination method.

Our triple phoswich (TPS) design is one approach to analyzing beta energy-deposition spectra (Bush-Goddard 2000). The concept simply involves layering three distinctly different scintillators on top of a photomultiplier tube. Low-energy betas (< 100 keV) will stop in the first layer, intermediate betas (100 keV – 1 MeV) in the second layer, and high-energy betas (> 1 MeV) in the third layer. Each scintillator has a unique scintillation decay time. By analyzing the decay time of the photomultiplier's output, some conclusions can be reached as to which layer(s) produced the signal. This provides a quantitative measure of the energy range of the betas incident on the detector.

Phoswich detectors have been used for a number of particle discrimination applications (Langenbrunner et al. 1992; Usuda 1992; Wang et al. 1994; Usuda et al. 1994a; Usuda and Abe 1994; Nagornaya et al. 1996; Usuda et al. 1994b) as well as gamma telescopes in astronomical investigations (Schindler et al., 1997; Qi et al. 1997a; Lum et al. 1997), mixed beta-gamma dosimeters (Vasil'ev and Volodin 1996), PET and SPECT components (Dahlbom et al. 1997), and heavy ion detectors (Fox et al. 1996; Qi et al. 1997b). A few researchers have examined unique variations of the phoswich detector, including a gas proportional phoswich (Benchekroun et al. 1993), detectors that utilize both scintillator and solid-state designs (Strauss et al. 1990), and well-counter phoswich configurations (Kamae et al. 1993). The use of three scintillators layered together is uncommon, but has been investigated primarily by Usuda et al. (1994a; 1997) at the Japan Atomic Energy Research Institute. These studies have shown that excellent discrimination between radiation types can be obtained, given the use of the appropriate scintillators and timing electronics.

Beta dosimetry and spectroscopy with plastic scintillators. Theoretical dose calculations are useful for purely predictive or retrospective analyses, but for real-world situations there must be measurement as well. We can roughly divide beta dose measurement into four categories: (1) dose derived from spectral measurements; (2) dose derived from “delayed” media such as thermoluminescent dosimeters and film; (3) dose derived from “immediate” media such as scintillators and ion chambers; and (4) dose derived from biological media such as hair diameter or skin erythema levels (ICRU 1994).

Scintillation dosimeters may be categorized by function: those that are used in laboratory or work settings to measure occupational dose; those that are used in medical settings for measuring patient dose; and those developed for special research purposes. In the lab or workplace, a common technique used to measure beta dose is to first measure the beta spectrum with a scintillator, and then calculate a dose from that information. Martz et al. (1986) used a plastic scintillator 2.5 cm diameter by 0.9 cm deep to measure beta spectra and convert those spectra to dose. They used a beta energy deposition function, derived from calibrated sources, to convert the measured spectra to dose at a depth of 7 mg/cm^2. Thus, calculation of dose relied not only on direct extrapolation of scintillator light output to dose, but on previously derived calibration curves, in order to isolate the dose to a thin layer at a specific depth. Gammas were excluded by measuring spectra with and without a beta shield. Shen et al. (1987) used plastic scintillators to measure spectra, from which they subsequently calculated doses using electron transport theory as applied to TLDs. Swinth et al. (1989) constructed a combination proportional counter-plastic scintillation counter for measuring beta spectra and dose. They used coincidence gating to exclude gamma events. Dose was calculated from spectral information and compared to extrapolation chamber data for calibration. Horowitz et al. (1993) developed a two-detector telescope device consisting of a thin silicon detector and a thick plastic scintillator. Again, gamma rejection was accomplished by coincidence analysis. Dose was calculated by comparison to Monte Carlo depth distributions for the spectra measured. Vapirev et al. (1996) employed a plastic scintillator to measure beta spectra after passage of the betas through absorbers of various thicknesses. Dose was calculated via specific energy losses, dE/dx, and the collected energy spectra. Results were compared to the calculations of Cross and Marr (1960).

In the medical setting, much of the effort has gone into dose measurements of high-energy photon beams (Beddar et al. 1992a, 1992b; de Boer et al. 1993; Mainardi et al. 1997; Clift et al. 2000). Though not measuring beta dose, the materials are the same, namely plastic scintillators coupled to a light detector and associated electronics. The complications are also similar, for instance, the need to account for Cerenkov radiation. Not all efforts have been directed towards photon radiation therapy: Bambynek et al. (2000) developed a dosimetry system for cardiovascular brachytherapy beta sources using a plastic scintillator; several authors (Williamson et al. 1999; Kirov et al. 1999; Fluhs et al. 1996) worked on plastic scintillator response to low-energy photons from brachytherapy sources; and de Sousa et al. (2000) studied a dosimeter for patients undergoing diagnostic radiology procedures. The primary advantages of plastic scintillator material in all of these cases are its near-water equivalence, a property useful when dose to tissue is desired, and small backscatter factors.

Several authors have studied thin plastic scintillators for beta dosimetry. Bingo et al. (1980) developed a beta dose survey meter using a 2 mm thick scintillator. The premise was that there existed a certain thickness of scintillator that would satisfy a directly proportional relationship between count rate and dose rate, for all beta energies, i.e. independent of beta energy. Two millimeters happened to be the experimentally determined optimum thickness. Johnson et al. (1983) deliberately chose to use a very thin plastic scintillator, backed by a 1 cm thick Lucite light pipe, to measure dose to skin directly. Kriss and Hamby (2003; 2004b) used thin sections of scintillator to estimate beta dose as a function of tissue depth. Finally, Watt and Alkharam (1995) proposed using extremely thin (20 μm) plastic scintillators to directly simulate

DNA damage, in the sense that the fluor spacing in the scintillator is analogous to the DNA diameter of around 2 nm. So, two scintillation emissions within 2 nm can be considered a double strand break, and thus an indication of dose.

Pulse-Shape Analysis. Some scintillators respond to different types of radiation (i.e., different rates of energy transfer) by emitting light with different timing characteristics. Likewise, different scintillators respond to the same radiation by emitting light differently. Because of these differences, a pulse-shape analysis (PSA) technique, or pulse-shape discrimination (PSD), can be performed to identify and selectively analyze the signal from either a particular radiation type (in two scintillators) or from a particular scintillator (with two radiation types). The majority of PSA/PSD systems operate on analog signal pulses; current technology, however, allows us to do more sophisticated analyses with the use of digital signal processing (DSP).

Traditionally, one of two approaches is used to perform the pulse shape discrimination for phoswich detectors. On the one hand, the rise time technique is based upon the integration of the light pulse (e.g. or the anode pulse of the phototube), followed by the determination of the time at which this integral reaches a certain fraction of its maximum. On the other hand, the charge integration method requires the comparison of the charge collected at the anode signal over two different time intervals, one normally encompassing the entire duration of the pulse, and the other limited only to a certain portion. Both methods are achieved using analog electronic systems.

Using fast ADCs, digital signal processing methods have gained popularity for analyzing signals from radiation detectors. The use of digital systems offers several advantages over conventional analog units, including digital pulse charge integration, reduced dead time, elimination of distorted pulses, noise analysis and minimization, and pulse shape discrimination capabilities. In our lab, we have developed a digital pulse shape discrimination algorithm specifically for a triple-layer phoswich detection system.

Digital signal processing. The digital processing approach has been demonstrated for:

1. improving energy resolution in γ-ray or X-ray spectroscopy through such methods as Compton continuum suppression (Aspacher 1994) or optimum filtering (Fazzi 1998);
2. obtaining digital pulse shape or pulse height spectra (Simes 1995);
3. improving throughput rates by using fast recursive digital algorithms (Jordanov et al. 1994) or reducing dead time (O'dell et al. 1999);
4. estimating the occurrence time of events for coincidence or anti-coincidence through least-mean-squares algorithms or linear algorithms (Geraci 1999); and
5. separating different radiation type-induced pulses in a phoswich detector by pulse shape discrimination (White and Miller 1999).

Although most of these applications utilized hardware implementation of digital signal processing algorithms, a more efficient alternative approach is to employ software algorithms as firmware. Software algorithms for pulse height, pulse shape discrimination, and dual parameter analyses have been developed by several research groups using digital oscilloscopes (White and Miller 1999; DeVol et al. 1999). The software implementation can be improved by decreasing process time with a fast digital signal processor; a particular CPU optimized for the digital signal processing. For prototyping, software implementation is performed using an appropriate digitizer, but once the algorithm for the signal processing is optimized, it can be translated to a firmware implementation form using field-programmable gate arrays (FPGA). Processed data by the FPGA then will be fed to a fast digital signal processor to drastically increase system throughput rate.

There are several advantages to digitally processing radiation pulses over the conventional analog approach (DeVol et al. 1999). For example: 1) the pulse processing algorithm is easy to edit, because changes are made through the software; 2) the algorithm is stable and reliable, since it is not affected by thermal noise or other fluctuations; 3) it is possible to make the detection equipment portable by eliminating most of the bulky analog electronics; 4) it is convenient to post-process the pulses; 5) it is more cost-effective; and 6) effects, such as pile-up (Chrien et al. 1986), ballistic deficit (Georgiev and Gast 1993) and charge trapping (Hess et al. 1994) can be corrected or eliminated at the processing level. Additionally, signal capture and processing can be based more easily on coincidence criteria between different detectors or different parts of the same detector (Warburton et al. 1999).

Within the digital domain, the software approach is much more versatile than the hardware approach. The major limitation associated with using software, however, is that it requires significant computation time to implement the algorithms (implemented by integrated circuits in the hardware approach). While this limitation has forced some applications to turn to off-line processing, increasingly faster analog-to-digital converters and computer processors have made on-line processing possible.

The Phoswich Design. In our research, we investigated the use of a 3rd generation triple-phosphor sandwich detector design for real-time, digital beta radiation spectroscopy and dosimetry in a mixed beta/gamma radiation field (Fig. 1). To facilitate pulse shape discrimination, the scintillators were chosen to have sufficiently different decay times (Table 1).

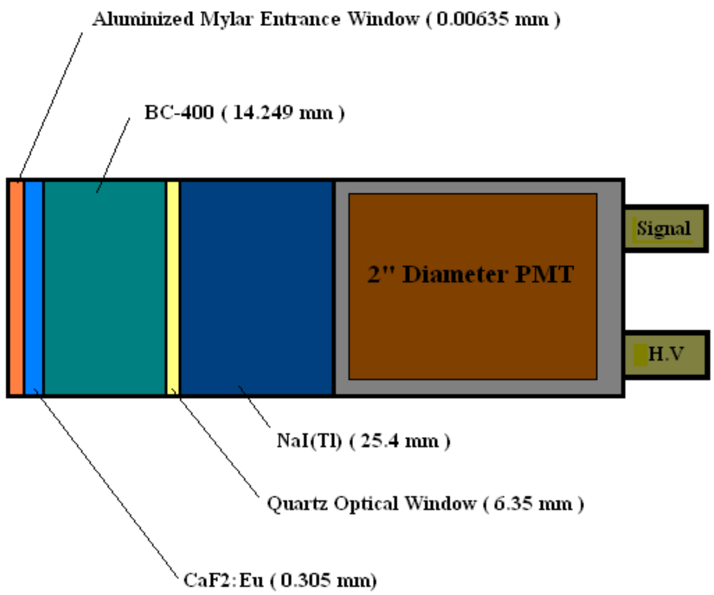


Figure 1. The 3rd generation phoswich design.

The first two layers of the detector are chosen specifically for beta spectroscopy, with the third layer intended for gamma-ray measurements. The first layer is a very thin plastic (BC-400) and the second layer is an inorganic (CaF_2:Eu); both are sensitive to beta radiations and their total thickness is enough to stop betas with energies up to 3.18 MeV. The thinness and density of the BC-400 scintillator minimizes the likelihood of gamma ray interactions and increases the probability that an incident beta particle will traverse the plastic and enter the inorganic scintillator before stopping.

Table 1. Scintillation material characteristics for the phoswich detector.

Scintillator	Density (g/cm^3)	Wavelength of Max Emission(nm)	Light Output % of NaI:Tl	Index of Refraction	Principle Decay Constant (ns)
BC-400	**1.032**	**423**	**26**	**1.58**	**2.4**
CaF_2:Eu	**3.19**	**435**	**50**	**1.47**	**900**
NaI:Tl	**3.67**	**415**	**100**	**1.85**	**230**

The design is such that the first layer must be penetrated by the incident betas for a pulse to be recorded as a beta-induced pulse. In other words, all slow pulses originating from the inroganic (CaF_2) scintillator without having a fast component (from the BC-400 layer) are rejected since they are considered to be gamma-induced pulses from interactions in the CaF_2.

The third layer (NaI:Tl) is a relatively thick inorganic scintillator and is included for gamma-ray measurements. Since plastic scintillators cannot be fully dried and would ultimately hydrate and destroy the performance of the crystal, the NaI:Tl shall be completely isolated by a thin quartz optical layer. The quartz acts as a light guide and does not affect the light produced in neither the CaF_2:Eu nor the plastic. In a mixed beta/gamma field, the energy distribution of gamma-rays detected by the NaI:Tl can be distorted by: (1) beta particles possessing enough energy to reach this layer; or (2) scattered gamma rays, due to Compton interactions originating from other layers (mostly from the CaF_2). Given the thickness of the first two layers and the quartz, only beta particles of very high energy (> 6.7 MeV) can reach the third layer. However, since absorption of scattered gamma-rays in the third layer produces a pulse with more than one timing component, the second interference can be eliminated by rejecting that pulse in an anti-coincidence filtering with other layers. The criteria for accepting or rejecting a given pulse are presented in Table 2.

Table 2. Criteria for accepting or rejecting pulses from the phoswich detector.

	Scintillation Layers			Relative Probability		Pulse Recorded as:
	1	**2**	**3**	Gamma	Beta	
1	×			**L**	**VH**	**Beta**
2	×	×		**VL**	**VH**	**Beta**
3		×		H	L	Rejected
4	×		×	L	VL	Rejected
5		×	×	L	VL	Rejected
6	×	×	×	L	VL	Rejected
7			×	**H**	**VL**	**Gamma**

[X] Pulse Detected; [L] Low Probability; [VL] Very Low Probability; [H] High Probability; [VH] Very High Probability

Methods

Beta dosimetry has long been studied in health physics and radiological engineering; other radiation types are generally straightforward in their dosimetric assessments, but accurate evaluations of localized energy absorption by beta emitters are quite demanding (Yokota et al. 1972; Quam 1983; Sherbini et al. 1985; Kocher and Eckerman 1987; Graham 1987; Tsoulfanidis 1991; Chung et al. 1991; Sigg 1996). The work herein utilized a prototypic phoswich detector, designed/developed in our laboratory, which can discriminate radiation type and energy by digital component analysis of signals from multiple scintillating layers and characterization of measured spectra for nuclide identification using neural network methods. State-of-the-art high-speed digital techniques are applied for enhanced spectroscopy and beta dosimetry.

The overarching research goal was the development of a radiation detection system capable of beta/gamma spectroscopy and computerized analysis for the simultaneous identification, quantification, and dosimetry of beta emitting radionuclides. The scope of the work conducted on this grant, as originally proposed, was limited to the comprehensive characterization of the prototype detector to various beta/gamma radiations, the development and implementation of an automated digital processing technique, and the incorporation of a neural network pattern recognition model for beta dosimetry in a mixed radiation field.

Summary of Project Activities

Phase 1 – MCNP Analysis of TPS Response. This Phase used Monte Carlo N-Particle (MCNP) software analysis to determine optimum operating parameters for the phoswich detector and set a basis for determining the optimum design of future detectors based on the original design. Tasks included:

A. *Determine energy spectra in each layer from monoenergetic electrons*

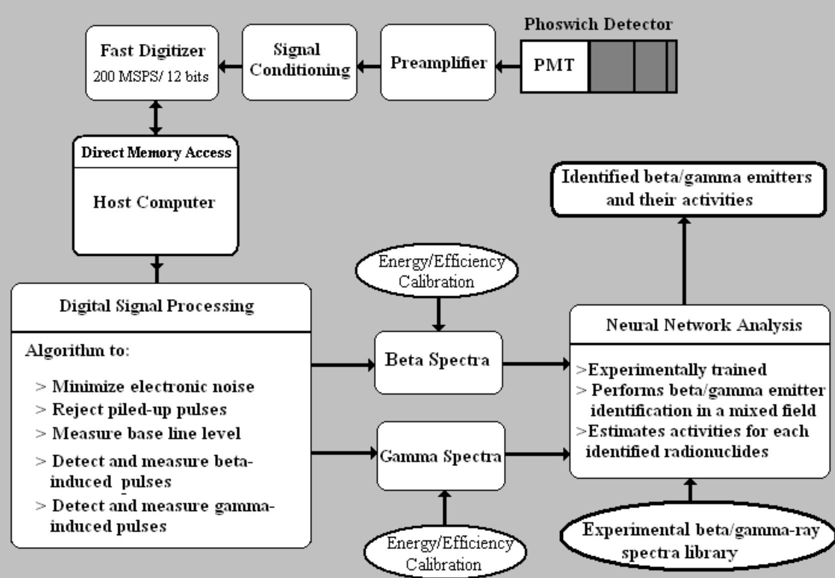
B. *Study the probabilities for possible combinations of radiation pulses*

C. *Optimize the TPS design for the best performance*

D. *Study possible procedures to minimize gamma-ray interferences*

Phase 2 – Digital Pulse Shape Discrimination and Analysis. Each analog signal from the phoswich detector is first fed into a preamplifier module. This module provides a current-to-voltage converter for incoming current signals. Voltage signals are then fed into a signal conditioning unit. The task of this circuitry is to adapt the incoming voltage pulses to the input voltage range of the digitizer. In order to avoid aliasing, the high frequency components from the incoming signal are removed by this unit prior to feeding it into the digitizer's ADC. The anti-aliasing filter cuts off at the Nyquist frequency, namely half the ADC sampling rate.

Figure 5. A preliminary scheme of the functions to be performed in the proposed research



The digitizer captures radiation-induced pulses with a sampling rate of 200 MSPS and 12 bits resolution. Multiple Record Acquisition Mode allows the system to be programmed to store a predetermined number of triggered pulses in the on-board memory independent of host computer operation. These stacked digitized pulses along their time stamps then can be transferred to computer memory using Direct Memory Access channel for digital processing. The major tasks of this phase included:

A. *Develop algorithm to reject invalid detected pulses*

B. *Develop algorithm to resolve convolved pulses*

C. *Compare different digital pulse shape discrimination (DPSD) methods*

D. *Optimize real-time measurement capabilities*

Phase 3 – Performance Study on the Spectrometer. In this phase, through experimental measurements, the spectrometer performance in measuring beta and gamma radiations was evaluated. The major tasks of this phase included:

A. Perform energy/efficiency calibrations for beta and gamma-ray interactions

B. Evaluate the system's radiation discrimination capabilities in a mixed beta/gamma radiation field

C. Compare measured beta spectra with theoretical spectral shape

D. Characterize the system throughput rate

Phase 4 – Beta Emitter Identification by Neural Network Formulation. This phase, being iterative, was devoted to neural network development and optimization. The major tasks included:

A. Develop neural network algorithm

B. First iteration of network analysis

C. Optimize network parameters

D. Develop input/output training datasets

E. Fine tuning and final network analysis

Phase 5 – Synthesis. In the synthesis phase, project components were unified into an automated, mixed-field, beta dosimetry system. The two major tasks included:

A. Develop automatic digital spectroscopy and unified network processes

B. Finalize system testing and packaging

Summary of Major Findings

MCNP analysis was used to simulate electron interactions in multiple scintillation layers. We employ the F8, or pulse height, tally to provide energy distribution of light pulses created in each scintillation layer for a given set of energy bins. Separate F8 tallies were defined for each scintillation layer to model energy pulses that would be generated in our triple-layer phoswich detector by beta interactions.

To study the timing characteristics of preamplifier pulses from the triple-layer phoswich detector, the MCNP-4B transport code was used to estimate the occurrence probability of the seven possible pulse types from monoenergetic electrons. For these calculations the energy threshold was assumed to be 20 keV so that events with energies less than this amount were excluded. MCNP was also used to study the energy deposition spectra in each layer of the phoswich detector from monoenergetic electrons. Simulated energy spectra in the first, second and third layers were accumulated. It was found that with increasing energy of electrons above 100 keV, the most significant component of the energy deposition spectra for the first layer shifts toward lower energy. This is a result of higher energy electrons passing through the first layer and depositing less energy in that layer. Additionally, interactions of electrons greater than 500 keV in the first layer generally add a small amount of fast decay component to the generated pulses.

The spreading of the peak deposited energies in the second scintillation layer resulted from electron attenuation in the first layer. The peak probability of each spectra increases with electron energy to 1 MeV, and then decreases. This can be attributed to the total thickness of the first two layers, a thickness designed to stop 1 MeV electrons. Energy deposition in the third layer reveals more spectral spread and softening than that of the second layer. Intrinsic efficiency for each layer as a function of electron energy was defined as the total probability that an entering electron of original energy E deposits its energy in that layer and produces a pulse with amplitude above a given threshold. With increasing electron energy beyond 500 keV, the intrinsic efficiency of the first layer arrives at a plateau, whereas the second layer efficiency has little change beyond 1.5 MeV. The third layer, however, does not show constant intrinsic efficiency in the studied energy region.

Based on our MCNP results, we developed a triple-layer phoswich with the following physical characteristics. The first two layers of the detector were chosen specifically for beta spectroscopy, with the third layer intended for gamma-ray measurements. The first layer is a thin plastic scintillator (BC-400) with very fast light-decay characteristics (2.4 ns); the second layer, an inorganic crystal (CaF2:Eu), has a very slow light-decay pattern (900 ns). Having low-Z materials, both layers are appropriate for beta particle detection and their total thickness is enough to stop electrons with energies up to about 3.2 MeV. The phoswich detector was designed such that an incident beta must deposit energy in the first layer, or in both the first and second layers, for a pulse to be recorded as a beta-induced pulse.

The third layer is an inorganic scintillator (NaI:Tl) with moderately slow light-decay characteristics (230 ns) and is intended for gamma-ray measurements. Given the thickness of the first two layers and the optical layer, only beta particles of very high energy (46.7 MeV) can reach the third layer, so that the light pulses generated in that layer represent gamma-ray interactions with no direct interference from beta particles of common beta emitters.

Simulations with MCNP show that Compton scatter is the prominent interaction mechanism from incident gamma-rays in the first two layers. Since the second layer is thick enough to accommodate electrons up to 3.2MeV, the unwanted events (mostly Compton scatter) in the beta side of the detector are comparable to that of the gamma side, the third layer. However, since common beta particles have much shorter mean free paths than gamma rays in scintillation materials, events in the first layer can be used to identify the beta-induced pulses from beta interactions with the second layer, and so the Compton events can be distinguished quite easily.

The PM tube output is connected directly, with no pulse integration, to our customized digital pulse processor (DPP). The DPP unit uses a fast analog-to-digital converter (ADC) with a 100 MHz sampling rate and 12-bit resolution. Digital and logic functions, such as over-range rejection, trigger control, partial pile-up rejection, and a circular buffer, are implemented in a field programmable gate array (FPGA). All communications, such as control commands and data transfers between software and the DPP, are performed via a high-speed USB 2.0 interface.

We developed a software algorithm to control the DPP and to characterize beta/gamma induced pulses. When a valid event occurs, the pulse stored in the circular buffer (with duration of 10.24 ms) is transferred to the host PC for further digital signal processing. A valid event is defined as the capture of a pulse possessing a duration and amplitude within a given range. Our custom algorithm processes the radiation pulse and if the pulse meets additional criteria, one of the energy spectra, beta or gamma, is updated.

For the purpose of pulse-shape discrimination, four quantities (baseline, P, M1 and M2) that described the basic shape of each pulse are measured. Then, the fast- (FR) and slow-component (SR) ratios of the captured signal pulse are determined. Using these ratios, the algorithm performs two inspections to predict whether the captured pulse is a gamma- or a beta-induced pulse, or whether it must be rejected because of its unknown conditions (e.g. Compton scattering from incident gamma-rays in the second layer). Two corresponding thresholds, obtained experimentally, provide the required criteria for these inspections.

Measurements indicate better gamma-ray discrimination from ^{137}Cs than from ^{60}Co. When the detector was exposed to ^{137}Cs, the algorithm identified 91.6% of pulses as gamma interactions and mischaracterized 1.8% of pulses as beta-induced signals. Also, 6.6% of pulses could not be identified and were rejected. However, most of the mischaracterized pulses during ^{60}Co measurements correspond by energy to Compton events, which result in the introduction of false-positive pulses in the beta spectrum. The rate of this effect was higher for ^{60}Co, presumably because of many more events at lower energies (mostly due to backscatter). Regardless of the beta mischaracterization, the algorithm was shown to be efficient at reconstruction of gamma-ray energy spectra. The resolution for the 662 keV photopeak of ^{137}Cs was measured to be approximately 6.7%. In all gamma-ray spectra, photopeaks have nearly symmetrical shapes and show other spectroscopic features; the backscatter peak, the Compton continuum, and Compton edge are prominent. Additionally, a peak is present at the low-energy region and was experimentally confirmed to be that of characteristic X-rays originating from excitation of the lead shield (70 keV).

The quality by which our algorithm discriminates beta induced pulses was evaluated by exposing the detector to pure beta emitters. The characterization algorithm shows better discrimination performance for low-energy beta emitters. At lower energies (e.g. ^{14}C), 98.8% of the pulses were identified as a beta event, while the fraction of gamma and rejected pulses was very small. For a high-energy beta emitter (e.g. ^{90}Sr/Y), however, the percentage of identified beta pulses was lower (70.1% as beta and 1.9% as gamma). Therefore, this pulse characteristic is not detected in the waveform inspection, and because of their slow-decaying shape, most of the pulses (in this case, 28.0%) were rejected as ‘‘unknown’’. In fact, the inspection algorithm mischaracterizes them as a Compton-induced pulse, which may originate from interactions of gamma rays in the second layer.

Regarding their end-point energies (E_{max}), the beta spectra show good energy calibration. However, their shapes are not quite matched with the shapes of their theoretical energy emissions. Possible reasons include instability in the threshold level due to baseline variations (this mostly effects the low-energy events); energy deposition in the air between the beta source and detector; energy deposition in the thin mylar cover; energy deposition in the gap between the first and second layers; and partial energy deposition in the scintillation layers themselves.

To evaluate the system for simultaneous beta/gamma spectroscopy, several beta/gamma source pairs were introduced to provide mixed radiation fields. Single beta/gamma sources were not used for both beta and gamma components because of a moderate amount of self shielding already present in the check sources and the inability to capture monoenergetic conversion electrons. By comparing beta and gamma spectra from the mixed fields with their corresponding spectra from gamma-only and beta-only fields, the capability of the signal discrimination process in preserving spectral information from both gamma and beta interactions in our spectroscopy system was confirmed.

Results

A real-time beta/gamma digital spectrometer has been developed, constructed and tested. The spectrometer allows the collection of beta and gamma energy deposition spectra, leading to dosimetry. The system utilizes a triple-layer phoswich detector, a customized digital pulse processor, and a characterization algorithm, all created in our laboratory. The MCNP software package was used to simulate the phoswich detector to establish important response characteristics to photons and electrons. When exposed to a mixed-beta/gamma field, the detector generates pulses, from which the type of incident radiation and the amount of energy deposited in each layer can be determined. Measurements indicate that the spectrometer is capable of discriminating among gamma and beta events, and successfully reconstructing the spectral information for each radiation type. The experiments show that the system has better discrimination performance for low-energy beta and gamma sources, while for high-energy radiations, relatively more pulses are mischaracterized or rejected.

The gamma-ray energy resolution at 662 keV of ^{137}Cs was measured to be as low as 6.7%, which shows good agreement with measurements using traditional NaI:Tl detectors; electron energy resolution was not measured at this prototyping stage. The shapes of beta energy deposition spectra were shown to be generally similar to theoretical emission spectra and to be similar to those obtained by Kriss (2004) who used a plastic scintillator and a large-area avalanche photodiode for beta-particle spectroscopy and dosimetry.

The design of this particular phoswich detector was not optimized for particular radionuclides. It is obvious, however, that the overall performance of the system could be significantly improved if the detector design is optimized for a specific application. For example, by decreasing the thickness of the second layer and increasing the thickness of the first layer, the system performance can be improved for the detection of a high energy beta emitter (e.g. $^{90}Sr/Y$), in the presence of a gamma-ray background. By this optimization, on average, high-energy beta particles transfer more energy in the first layer and consequently, both the mischaracterizations and pulse rejections due to high-energy beta particles would be decreased significantly.

Products Developed

The PI and his students have authored a number of publications and presentations regarding the work described above. Several short software routines also have been written during the study. One doctoral student has earned his degree as a direct result of this work, while several Master's students gained experience and support while providing necessary input and background research to this project. Several Monte Carlo simulations of the triple-layer phoswich detector were developed and studied to provide insight into the interaction mechanisms in each scintillating layer. Layer thicknesses were optimized for general beta/gamma spectroscopy. And, finally, a neural network foundation has been established for aiding in the identification of beta sources.

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Farsoni, A.T.; Hamby, D.M. An FPGA-based data acquisition system for a multi-layer phoswich detector. IEEE Nuclear Science Symposium and Medical Imaging Conference. Honolulu, HI. October 27 – November 3, 2007.

Hamby, D.M.; Farsoni, A.T. A system for simultaneous beta and gamma spectroscopy and its application to nuclear non-proliferation. International Safeguards Workshop for Advanced Sensors for Safeguards. International Atomic Energy Agency. Santa Fe, NM. April 23-27, 2007.

Farsoni, A.T.; Hamby, D.M. A system for simultaneous beta and gamma spectroscopy. *Nuclear Instruments and Methods in Physics Research - Section A.* 578: 528-536. 2007.

Farsoni, A.T.; Hamby, D.M. Proof of concept for a digital phoswich spectrometer. Proceedings of the Fifty-second Annual Meeting of the Health Physics Society. Portland, OR. *Health Physics*. 93(1): S102; July 2007.

Farsoni, A.T.; Hamby, D.M. Prediction of possible anode pulse shapes due to gamma/beta interactions in a multilayer scintillation detector using MCNP simulation. *IEEE Transactions on Nuclear Science*. submitted. June 2007.

Hamby, D.M.; Farsoni, A.T. A system for simultaneous beta and gamma spectroscopy and its application to nuclear non-proliferation. International Safeguards Workshop for Advanced Sensors for Safeguards. International Atomic Energy Agency. Santa Fe, NM. April 23-27, 2007.

Farsoni, A.T.; Hamby, D.M. Simultaneous Beta and Gamma-Ray Digital Spectroscopy Using a Triple-Layer Phoswich Detector. 2006 Nuclear Science Symposium. Medical Imaging Conference and 15th International Room Temperature Semiconductor Detector Workshop. IEEE. San Diego, CA. Oct. 29 – Nov. 4, 2006.

Farsoni, A.T.; Hamby, D.M. Study of a Triple Layer Phoswich Detector for Beta and Gamma Spectroscopy with Minimal Crosstalk. NNSA Seismic Research Review. Orlando, FL. September 19-21, 2006.

Hamby, D.M.; Farsoni, A.T. Phoswich Detectors and Digital Pulse Analysis for Simultaneous Beta/Gamma Spectroscopy. Western New York Chapter of the Health Physics Society. Buffalo, NY. April 21, 2006.

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